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PROBLEM ANALYSIS

FOREST FIRE BEHAVIOR RESEARCH

CALIFORNIA FOREST AND RANGE EXPERIMENT STATION

By[1]/

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1/ The original outline of this analysis was prepared in conference by H. D. Bruce, W. L. Fons, and the authors.

TABLE OF CONTENTS

	Page
Introduction	1
I. Definition of fire behavior	1
II. Fire behavior research objectives	2
Relation of fire behavior research to the problems of forest fire protection	2
General	2
III. Classification of the field of fire behavior research	3
Ignition studies	4
Spread studies	5
Miscellaneous studies	7
Fundamental studies	9
IV. Present status of fire behavior knowledge	10
Ignition	10
Spread	11
Miscellaneous	11
Fundamental	11
V. Review of fire behavior studies at the California station	12
Ignition studies	12
Spread studies	12
Miscellaneous studies	13
Fundamental studies	15
VI. Clarification of objectives as dictated by fire control needs	17
Current problems requiring fire behavior study	18
Contribution of specific behavior studies to the problems listed above	19
VII. Research policy	19
Place of behavior studies at the California station in the solution of local and national fire control problems	19
Long-term behavior research objectives	20
Practical vs. fundamental approaches to behavior research problems	20
VIII. Three-year behavior research plan	22
General	22

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Page

IX. Assignment of studies 25
Responsibilities of men assigned to studies . . . 25
Assignments 25

X. Work plan development 26
General 26
Elements of a work plan 26
Work plan revisions 27

XI. Annual working plan conference 27

Appendix I
Principal factors influencing fire ignition . . . 28

Appendix II
Principal factors influencing rate of spread
of forest fires 29

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By John R. Curry and C. C. Buck

INTRODUCTION

Forest fire research is concerned with the study of forest fires and with the development of methods and techniques in fire control, a major problem in the management of American forests. Three phases of forest fire research are commonly recognized: attack, or means of directly improving fire control practice; behavior, or the influence of natural factors on the start and development of fires; and damage (or effects), the results of fire upon forest resources. Current forest fire research at the California Forest and Range Experiment Station is devoted to the first two. The attack project is engaged in the solution of specific problems of immediate importance to fire control practice within the Region. The behavior project, on the other hand, is engaged mainly with the discovery of those fundamental principles, governing the start and spread of fires, which are essential to a full understanding of the fire problem and to adequate fire control.

In the approach to any major research project an analysis is desirable to divide the field into sub-projects and into studies. Such analysis permits a more logical and fruitful attack in permitting the solution of the main problem through its division into a series of simple problems. If carefully developed this procedure will improve efficiency through the elimination of confusion as to the scope of the field and through removal of tendencies toward duplication or incorrect emphasis.

This analysis of forest fire behavior is made after several years of experience in research in this field. It is conceived and developed to serve as a guide to the future development of the forest fire behavior project at the California Station. It attempts to define, insofar as possible, specific problems to be solved, and to describe the sequence of studies required in the solutions. Detailed study work plans are not considered a part of this analysis; the form of such plans is, however, discussed in one section of this report.

I. DEFINITION OF FIRE BEHAVIOR

Forest fire behavior is the manner in which forest fires ignite, spread, and exhibit other phenomena. The study of fire behavior is concerned with the determination and evaluation of the influences of all the pertinent factors upon the manner in which fires are established and spread in forest fuels.

II. FIRE BEHAVIOR RESEARCH OBJECTIVES

Relation of Fire Behavior Research to the Problems of Forest Fire Protection

The organization of adequate forest protection facilities requires the application of sound knowledge of fundamental principles of fire behavior and fire damage. It is thus essential to the promotion of efficiency in forest protection that knowledge of at least certain phases of fire behavior be specific - based upon broad experience, results of experimentation, or combinations of both. It is the purpose of fire behavior research to supplement experience through acquisition of factual information derived from detailed study of specific behavior problems.

General

The general objective in forest fire behavior research is the recognition, measurement, and correlation of the factors which influence forest fire phenomena to the end that the behavior of fires may be adequately predicted under all common forest conditions. This broad objective is divided below into a series of specific objectives, each covering a phase of the field in an orderly progression from the determination of fire control problems to the ultimate application of results in their solution.

1. To recognize the behavior problems of importance in fire protection.

The success of fire behavior research depends upon its ability to produce results of practical application to both immediate and long-time problems in the field of fire control. It is essential, therefore, that a broad program of fire behavior research be based upon adequate consideration of major problems in the fire control field to which behavior research can make most valuable contributions.

2. To recognize the fundamental variables concerned with fire behavior.

This objective follows directly from the definition of forest fire behavior research as the study of all the pertinent factors influencing fire behavior.

3. To measure the fundamental variables concerned with fire behavior.

Following recognition of the variables concerned, methods of quantitatively measuring them as they influence fire behavior must often be developed. As an example, physical fuel variation is a recognized primary variable in fire behavior, but no method has been devised for quantatively measuring its influences.

4. To evaluate and correlate the influences of fundamental variables on fire behavior.

This is the major step in all fire behavior research. It involves elimination of those variables not having significant influences, the sorting out of those of importance and finally their integration into measurable results.

5. To point out the application of knowledge gained to fire control problems.

This step is concerned primarily with the adaptation of experimental results to the practical problems of fire control and with the development and promulgation of basic principles of fire behavior which have broad application in the fields of presuppression and suppression.

6. Selling practical results.

This step has been demonstrated to be of importance in other fields and is no less important in fire behavior research. In order that such research may result in improved practice, fire control men must be shown the advantages to be derived and trained in proper applications.

7. To acquire as much factual knowledge as possible.

The experience of fire control men provides the first source of fire behavior information. It is held, however, that efficient progress in this field is dependent upon a better understanding of the factors controlling forest fire phenomena than experience alone will provide and that any approach which disregards this field of study abandons those tools of science which have hitherto laid the foundations of progress in forestry. To the end that forest fire protection as a part of the forestry science may be placed upon a broad factual basis, one of the prime objectives of this type of research should be to compile and make available to the field a maximum amount of basic factual information.

III. CLASSIFICATION OF THE FIELD OF FIRE BEHAVIOR RESEARCH

Fire behavior research is divided for convenience in organization and administration into four phases (a) ignition, (b) spread, (c) miscellaneous phenomena, and (d) fundamental studies. In specific instances overlapping of the various fields exists, but, in general, all studies fall into one of these four classes. While it may be assumed that foresters are primarily interested in the ignition and spread of fires, it will be shown in the discussion of the individual classes that all play an important role in the attack on the fire problem.

Ignition Studies

Definition

The study of forest fire ignition is the evaluation of the influences of (a) fuel characteristics, (b) weather, (c) firebrands, and (d) other physical factors except man upon the inception of forest fires. From this evaluation, a better understanding of the probability of fire occurrence as it is influenced by these controlling measurable variable factors should be forthcoming.

Types of Ignition Studies

The ordinary concept of forest fire ignition distinguishes between two fire starting agencies; man and lightning. From the fire research standpoint, however, the field of fire ignition can better be divided into five groups of studies, some having to do with evaluation of basic physical factors of general application, and others with specific problems. The five groups are briefly outlined as follows:

1. Theoretical analysis of ignition.

Ignition studies in this field are primarily concerned with the application of fundamental combustion information to the problems of forest fire ignition.

2. Studies of the influences of single factors and factors in simple combinations on fire ignition.

Because of the complex action and interaction of the various factors influencing forest fire ignition, it is essential that simple relationships be determined prior to the ultimate correlation of all factors concerned. In this category fall studies of the influences of the following factors:

1. Fuel moisture
2. Physical characteristics of fuels
3. Chemical composition of fuels
4. Weather factors:
    (a) Temperature
    (b) Wind
    (c) Humidity
    (d) Insolation
5. Types of firebrands

In addition to these factors, others less well understood at present may warrant individual treatment.

3. Studies of the influences of combinations of factors on fire ignition.

In this group are studies of the combined influences of selected groups of factors and of all the factors listed above. Studies in this group are of two types:

1. Controlled ignition tests

2. Studies of actual fire ignition

4. Special problems in ignition.

Two types of studies are now recognized which fall into this group:

1. Influence of lightning on fire ignition by:

   (a) Occurrence

   (b) Kind

   (c) Intensity

   (d) Elevation

2. Influence of green vegetation on ignition.

5. Miscellaneous studies of ignition.

In this group fall studies incidental to research in the other phases, or studies not primarily concerned with the direct measurement or field evaluation of the factors enumerated above. Statistical analysis of ignition data from forest fire records falls within this group.

Spread Studies

Definition

The study of rate-of-spread may be defined as the evaluation of the influence of all important factors upon the growth of fire in fuels composed of natural vegetation. Although the ultimate factors influencing fire spread are not known, three general classes of factors are recognized; fuel (size, arrangement, composition), weather, and topography. The objective in these studies is to discover and define the fundamental relationships which will permit generalizations on the size which a fire will attain under any range of the influencing factors.

Types of Spread Studies

In the study of a complex natural phenomenon of this type, a logical approach involves several types of studies. Four general classes of studies are recognized in this analysis: (1) theoretical studies, (2) studies of the influence of single factors or simple combinations of factors, and (3) studies involving all or most factors in complex combinations. Each class of study will be briefly discussed.

1. Theoretical studies.

The phenomenon of a spreading fire may be considered the combustion of cellulose fuels under conditions involving the action and reaction of a complex group of natural factors. The problem may be considered as simply the application of the known physical laws governing combustion to the natural and complicated conditions under which these fires occur. An analysis of the problem of spread starting with the physical laws governing combustion and the amassed information on the characteristics and composition of cellulose materials is the first step in the study of rate of spread. Such an analysis is particularly valuable in isolating the factors concerned and in suggesting studies leading to clearer definition and more precise measurement of the individual factors involved. Theoretical studies can seldom indicate the precise influence which any factor has. They serve, therefore, mainly to lay the broad foundation for other studies in the search for precise expression of factor influence.

2. Determination of the influence of single factors and factors in simple combinations.

In a complex problem the influences of each of the many factors involved cannot be immediately isolated, measured, and described. For this reason it is frequently desirable to test the influences of single factors or simple combinations of factors by eliminating or controlling others. Such studies require either adequate laboratory facilities or the adaptation of laboratory methods to field study. Adequate laboratory facilities for rate-of-spread research include humidity, slope, and wind control. Such facilities are nowhere available. Although the availability of such facilities would undoubtedly promote behavior research, their absence does not entirely remove possibilities of using laboratory methods.

Valuable results have been obtained in testing the influence of slope under uniform conditions of humidity and wind velocity. Experiments with wind and fuel moisture held uniform have also been productive of better understanding of the fuel factors of importance to rate of spread. In a like manner, the influence of many of the other factors involved can be originally tested under controlled conditions. Danger exists in considering results of such studies as more than indicative of the general form of the relationship established by the study. The scale of such experiments and the absence of any means of judging the importance of joint correlation with other variables make it necessary to establish final relationships on the results obtained from more comprehensive studies discussed below.

3. Studies of the influence of factors in complex combinations.

In finally establishing rate-of-spread relationships, recourse must be made to studies under complex field conditions where all or most of the important factors are present and where the interactions of variables may be measured. In general, two avenues are open for the final determination of rate-of-spread relationships. The first method involves the study of fires started for the express purpose of study, and controlled following the study period. The second method utilizes uncontrolled spreading fires as a source of rate-of-spread data.

The test fire method permits the experimenter to choose in a general way the conditions under which the test is run. Furthermore, the number of tests is limited principally by the risk involved and the suppression facilities available. The size of the test fires can seldom be large and tests of this kind are relatively expensive.

The study of going fires can never be reduced to a systematic basis due to the impossibility of determining the time and place of fire occurrence. The data collected, because of obvious limitations of the method, must often lack refinement and accuracy. Only a few fires can be so studied in any one year and in some years little or no data could be obtained from this source.

Data for generalization under natural conditions must come in general from test fires. Test fire studies cannot be complete, however, because the relationships established on small fires may not apply to fires of greater size. To test the application of relationships under serious conditions, study of going fires will be necessary.

Miscellaneous Studies

A number of studies though not directly related to fire ignition or fire spread hold promise of furnishing information of value in fire suppression. The following are recognized studies in this group, set up to solve specific fire behavior problems or to explain observed phenomena, the understanding of which will directly benefit fire suppression.

Influences of Fire

This group of studies has been set up to answer specific problems concerning the influences of fire on adjacent fuels, and on local weather conditions. The influence of fire upon these elements has an important bearing upon the credence which can be given to weather forecasts in fire suppression and also upon the measurement of these factors on going fires.

Crowning

While the progress of crown fires may be conceived as one phase of fire spread, two phases of crowning not directly related to spread are recognized for special study. These are:

1. Determination of the circumstances leading to the ascension of flames into the crowns

2. Determination of the conditions essential to spread of fire through crowns

Spotting

The spotting of fires is a fire behavior phenomenon of great significance in fire suppression. While one phase of spotting is directly related to fire ignition, several features of the problem warrant separate study. Among possible studies the following are of particular importance:

1. Distance and distribution of firebrands

2. Type of firebrands

3. Temperature of firebrands

Behavior of Corralled Fires

Studies in this group are for the purpose of increasing available knowledge of the characteristics of corralled fires which may be used to improve the mop-up and patrol phases of the suppression job. Specific studies suggested in this field are:

1. Behavior of fire in logs

2. Behavior of fire in snags

3. Behavior of fire in duff

4. Behavior of fire in roots

Behavior of Ground Fires

Because of their unique characteristics, the behavior of ground fires is considered to be best attacked as a separate problem. Although infrequent in California, these fires are of considerable importance in other Regions. Studies of recognized importance in this field are concerned with:

1. Types of fuel

2. Ground fire ignition

3. Spread characteristics

Fingering

The problem of fingering is confronted on most major fires, and frequently is the cause of serious breaks either from the increased perimeter or from the large amount of unburned fuel left within the control lines. To recognize the conditions contributing to the phenomenon and to develop improved suppression technics where it occurs, the following studies should be made:

1. Types in which fingering occurs

2. Influence of fuel conditions

3. Influence of weather conditions

4. Influence of topography

Special Problems in Combustion

This group of studies is concerned primarily with the kinds and relative quantities of fuels and of oxygen involved in the combustion process of forest fires. These studies are important in providing basic information for studies of fire intensity in relation to the effects of forest fires.

Fundamental Studies

Before problems in the foregoing fields can be solved, certain studies must ordinarily be undertaken to determine (1) the factors involved, (2) their measurement, and (3) their behavior or variation under natural conditions. Studies in this category, primarily concerned with the isolation and measurement of the individual factors, have been classified as fundamental.

Fundamental studies have wide application to many problems. This fact, together with the serious lack of information on the factors influencing fire behavior, justifies the recognition of this major field of study.

Below are listed the important groups of fundamental studies recognized in this analysis:

1. Studies of principles of combustion

   (a) Elements of combustion
   - Essential conditions
   - Kinds of fuel
   - Oxygen supply
   - Heat transfer

   (b) Products of combustion
   - Smoke
   - Light
   - Heat
   - Gases

2. Studies to determine factors influencing combustion.

   In Appendix I of this report are listed the factors which are now recognized as influencing ignition and rate of spread. Fundamental studies are required to complete this list of factors and to indicate their relative importance.

3. Studies to determine methods of measuring factors of importance in fire behavior

   Examples:

   (a) Measurement of physical fuel factors

   (b) Measurement of fuel moisture

4. Studies to determine behavior of individual factors under natural conditions

Examples:

(a) Fuel moisture and weather relationships

(b) Seasonal and short time variations in wind movement

(c) Variations in physical fuel factors with season or weather

IV. PRESENT STATUS OF FIRE BEHAVIOR KNOWLEDGE

The present store of knowledge on the influences of the many factors upon all phases of fire behavior is meager. Considering the breadth of the field and the limited number of men engaged in fire research, however, considerable progress has been made. The purpose of this section is not to give a complete resume of all the results which have been attained, but rather to summarize in a brief and general way the major accomplishments in the different classes of studies, ignition, spread, miscellaneous, and fundamental.

Ignition

As long ago as 1909, experiments were conducted at Purdue University on the ignition of fires by railroad locomotive sparks. These and subsequent studies were primarily concerned with the size, temperature and effective distance of travel of sparks, and some of the fuel relationships involved.

During the period 1915-1917 Show conducted tests in ponderosa pine-needle litter to determine the influence of fuel moisture content upon the possibility of starting fires with matches. His technique was to soak litter in water and make periodic inflammability tests as it dried out. Moisture content values were approximations, probably on an air-dry basis.

During later years Gisborne, Stickel, and others working with more refined methods determined the ranges of moisture contents in which different kinds of firebrands would start fires in different kinds of fuel. Although the maximum moisture content limits at which various firebrands are effective have been defined in these studies, no information is yet available on the probability or chance of a particular firebrand causing ignition under specified fuel and moisture conditions. Some work has been devoted to the study of critical fuels indicating the characteristics of the fuels which make them particularly susceptible to ignition.

Fairbanks and Bainer at the University of California have carried on intensive investigations on the size and temperatures of carbon particles which start fires in various common California fuels, including grain stubble, grass, ponderosa pine needles and brush litter. Moisture content and surface fuel temperatures were other variables considered in

this study. The results, expressed in diagrammatic form, give for each series of tests the conditions of the test, number of trials, and number of actual ignitions. These experiments, made in conjunction with the development of spark arresters for internal combustion motors, were carried only far enough to satisfy this practical requirement.

Spread

Show, in the period 1915-1917 was the first worker to employ the test fire technique in the study of factors influencing rate of spread. His major conclusion was that fire tends to spread as a function of the second power of the wind velocity. Later work at the California Station fails to confirm this conclusion if the influence of moisture content of the fuel is isolated. Under normal summer fire weather conditions in the California pine region, however, moisture contents are low when wind velocities are high and, conversely, moisture content is high when wind velocity is low. Thus the conclusion drawn from the early data is ordinarily consistent if wind velocity alone is taken as the sole basis for prediction. Because the wind and moisture relationship is subject to material fluctuation this generalization holds true only on the average day.

In addition to the intensive test fire studies at the California Station summarized in the next section, several investigators have employed the same technique in the solution of various rate-of-spread problems during recent years. The most intensive of these have been the studies of the Southern Station on the relation of weather and fuel conditions to fire behavior, to develop an improved technique of controlled burning.

The study of going fires has never been developed to make full use of the information which may be obtained. The greatest advances in this field have been made in Regions 1 and 6 where Gisborne and McArdle, respectively, devoted considerable time to the relation of behavior of going fires to current weather conditions. Notable among these are Gisborne's observations of the Priest River Fire in northern Idaho and those of McArdle on the Tillamook Fire in western Oregon.

In addition to the field studies of going fires, numerous statistical analyses have been made on the relationship of the occurrence and behavior of fires to recorded weather conditions, both seasonal and short period.

Miscellaneous

Practically no recorded information exists on the influences of the behavior factors upon the miscellaneous fire phenomena previously listed.

Fundamental

The contributions of fire control investigators and others to the group of studies classified as fundamental, though not numerous, are of great importance to present research.

The various studies of weather and fuel moisture relationships originated by Show and subsequently carried forward by Gisborne, Dunlap, Stickel, and others have been most productive of fundamental knowledge of direct application in the fields of fire control research and practice. Recent work in this field at the California Station is summarized in the next section.

In addition to this experimental work, some valuable contributions have been made through theoretical approach to the combustion problem. Notable among these are Hawley's analysis reported in the Journal of Forestry in 1926, and Gray's unpublished report on the theory of combustion in its relation to the behavior of forest fires, prepared in 1933.

Outside the field of forest fire research, a large volume of unassembled information concerning the elements and principles of combustion exists in the literature of commercial fuels. While little of this information is of direct application, many of the principles and much of the experimental technique may be adapted to the study of forest fire behavior problems.

V. REVIEW OF FIRE BEHAVIOR STUDIES AT THE CALIFORNIA STATION

During the period 1915-1917, Show working at Feather River, originated fire behavior studies in the California region. The major accomplishments of this early work and the more detailed recent investigations in California are summarized on the following pages.

Ignition Studies

Only a limited amount of attention has so far been given to the ignition phase of fire behavior research in California. Show's early work in determining the ignition of litter is described in the preceding section. Mention has also been made of the tests reported by Fairbank and Bainer on the inflammability of graded fuel sparks in several common fuel types.

Spread Studies

Recent research in fire behavior at the California Station has been confined principally to the field of rate of spread, both through the use of test fires and through fundamental studies designed to provide a clearer understanding and better measurement of the governing factors.

Test fires

The tests conducted by Show at Feather River were the first studies attempted in this phase of fire behavior. From 1917 to 1933 no research was reported in this field. The study of spread was resumed in the latter year to provide: (1) data for a study of the factors controlling time and distance relationships governing the detection of fires from lookouts; and (2) to determine more accurately the influence of fuel moisture and wind velocity upon fire spread.

For the purposes of the detection study a large number of small fires were required at various distances and directions from a central lookout station. It was possible in most cases to select dense stands of young ponderosa pine providing a relatively uniform fuel condition, with little or no grass, ground cover, or reproduction. Approximately 200 fires were studied during this season. The period of study varied from 8 to 30 minutes with a modal time of 16 minutes.

Data were obtained on fuel moisture, wind velocity, and perimeter by 2-minute periods. All fires were on level ground. These data offered considerable promise in the definition of spread relationships, although the length of the burning period formed a serious limitation to their usefulness. After preliminary analysis, further studies were planned for a period of 30 minutes and under certain fuel, moisture, and wind conditions not encountered in the initial work. During the 1934 field season, therefore, a total of 86 larger fires were studied. Forty-eight of these were on slopes; 38 on level ground.

In the fall of the same year studies of the influence of slope on spread were conducted in the laboratory.

The accuracy of the field data was limited by natural conditions and by lack of satisfactory techniques of factor measurement. It was impossible to obtain, for instance, an equitable distribution of fuel moisture and wind velocities. High wind velocities were ordinarily experienced only with low fuel moistures while low wind velocities were normally accompanied by high moisture values. The number and size of the fires were limited by the difficulty of finding sufficient plots with uniform fuel conditions, and by the suppression effort required. Fuel variations were eliminated insofar as practicable by choosing plots of uniform appearance, but with the most careful selection, it was recognized that some variation in this factor existed. Wind velocities encountered were low, never exceeding 5 miles per hour. Errors were discovered in the early methods of wind measurement. The technique of fuel moisture measurement varied somewhat throughout the tests. Later studies have demonstrated that appreciable variation might be expected in this factor under conditions where the exposure to weather appeared uniform. Methods used in determination of fuel moisture content were later found to be relatively inaccurate.

In the preliminary analysis, the tendency of fires to spread at an increasing rate with time, other factors being uniform, became apparent. Time was therefore considered a third independent variable.

The influence of wind was next found to be strongly affected by the time factor. This presence of joint correlation necessitated the abandonment of standard methods of multiple correlation analysis. In the final analysis special methods adapted to problems of joint correlation were utilized. The results will be published shortly in the Journal of Agricultural Research.

The analysis provides the following information on surface fires in ponderosa pine litter:

1. Curves of the influence of fuel moisture content on perimeter increase (feet per minute) within a range of 3-13 percent.

2. Corresponding curves of the influence of wind velocity, range 0-5 miles per hour.

3. Curves of the influence of time for the period 2-22 minutes through the above ranges in fuel moisture and wind velocity.

4. Curves of the combined influence of wind velocity and slope on rate of spread.

5. Curves of the approximate total perimeter of fires under all common fuel moisture and wind conditions to 22 minutes.

6. Empirical formulas for the estimation of rate-of-spread and total perimeter.

Due to limitations of the data, none of the relationships derived in this study are considered finally established. All are subject to extension and modification by studies conducted under a wider range of conditions and with refined technique before they may be accepted as final.

The experience gained in this study demonstrated the need for careful research in the definition, behavior, and measurement of the individual factors as a fundamental need in this field. Accordingly, later research has consisted largely in detailed studies of the measurement of wind and fuel moisture, together with studies on the diurnal and seasonal ranges and variations of these factors. In recognition of the importance of the fuel factor, research on the physical characteristics of governing spread has been undertaken. These are discussed in a following section on fundamental studies.

Although principal emphasis has been placed on the study of fundamentals, test fires have been undertaken since 1935 in a northern California brush stand. Test fires were planned for this type because of: (1) its outstanding importance in the California protection problem; (2) its uniformity; and (3) the desirability of securing information on the behavior of simple crown fires.

In all, 33 fires have been studied in a uniform stand of brush consisting principally of manzanita (Arctostaphylos sp.) and snowbrush (Ceanothus velutinus). Several new problems have been encountered here, viz.: (1) the measurement of fuel moisture in the variety of green and dry fuels present; (2) the irregularity of burning, requiring the use of forward spread in place of perimeter; and (3) the need for a method of classifying fuels in the present absence of a precise method of measuring the physical fuel factor. These problems all indicate the need for additional studies of the type classified here as fundamental.

In the preliminary analysis, 8 fires were eliminated from consideration because of erratic behavior, presumably caused by fuel variation. No generalization could be made in regard to the initial spread or starting time of the remainder. The crown fire usually developed only after the surface fuel had been consumed for a distance of 8 to 12 feet from the starting point. Following the starting period, the fires burn with some degree of regularity dependent upon wind and moisture conditions. During this latter period, therefore, small variations in fuel apparently have less influence on spread.

No generalizations are possible on the influence of fuel and moisture factors on rate of spread with the present limited data. At least 3 times the present data will be required to permit correlation studies of these variables. Future studies of spread in this type should be carefully planned to provide data over a wide range of independent factors.

In addition to the ponderosa pine and brush types, a small amount of data is available on fires under selected fuel conditions in the white fir and lodgepole pine types.

Going Fires

Of recent years attempts to obtain rate-of-spread data for southern California conditions have resulted in the preparation by lookouts of maps showing rate of spread by time intervals. Information on the independent variables, wind, slope, and fuel moisture are unavailable.

The study of going fires has wide application to fire behavior studies. The principal drawbacks to the use of this technique are the infrequency of fire occurrence and the difficulty of accurate measurements. After the establishment of the basic principles of fire behavior through the use of test fires, going fires should be used to test these principles under the more serious conditions of a large spreading fire.

Miscellaneous Studies

No recorded studies in this branch of fire behavior research have been conducted in California.

Fundamental Studies

Fundamental fire behavior studies conducted currently and in the past at the California Station have been confined to studies of wind movement, fuel moisture, and forest fuels. The work done on each is summarized briefly below.

Fuel Moisture and Weather Relationships

During the period 1915-1917 Show demonstrated that litter fuels varied in moisture content with corresponding variations in relative humidity independent of precipitation. Approximations were made of the normal range of variation associated with relative humidity changes.

Beginning in 1935, more detailed investigations of the weather and fuel moisture relationships were undertaken employing improved techniques developed in the meantime. During the three-year period since the start of this study, sufficient data have been accumulated to demonstrate that time and insolation, together with relative humidity, exert an important influence on fuel moisture. Most of the data collected thus far have been concerned with variations in surface litter moisture content and their causes on small areas at different hours of the day and at different periods of the fire season. Current data are being gathered on seasonal and diurnal variations in green brush foliage.

Determination of Fuel Moisture

During the 1935 field season the large forced-convection drying-oven employed in routine fuel moisture work was found to be unsatisfactory for the determination of the small but significant differences in moisture content of field samples. The following winter a laboratory study in drying technique was designed to determine more satisfactory methods. This resulted in selection of the reflux-distillation method and the construction of a 6-unit apparatus for use in routine determinations. A detailed study of the comparative results obtained by this and other methods, resulted in the establishment of xylene distillation results as a basis for all fuel moisture determinations.

Studies of Wind Movement

The necessity for measuring relatively low wind velocities on ponderosa pine test fires resulted by 1935 in the development and adaptation of certain sensitive wind measuring instruments not previously used in such studies. These instruments together with Weather Bureau type 3-cup anemometers for measuring higher velocities were employed during the ensuing 2-year period in three studies: (1) horizontal variation in wind velocities 30 inches above ground in second growth pine; (2) vertical distribution of wind velocities in the open, and in pine and brush stands; and (3) relationship of wind velocities at three widely separated points on the McCloud Ranger District, Shasta National Forest.

The first study was conducted as a means of determining the number and distribution of anemometers required to obtain satisfactory measurement of wind velocity influencing the spread of test fires. A satisfactory technique for these measurements was developed and the study has been concluded.

The second study, in the vertical distribution of wind velocity, was designed to determine the relationship of velocities measured outside or above timber and brush stands to velocities at different elevations within the stands, and to determine the most satisfactory height above ground for measuring wind movement on test fires in the pine and brush types. Typical curves of velocities at various elevations above and within the stands were obtained for a range of wind velocities measured above the crowns. The study resulted in acceptance of a height of 30 inches above ground as the most satisfactory point to measure wind velocity on test fires in the pine type, and a point approximately 2 feet above the average crown height in the brush type.

The third study was conducted to determine the relationship between wind velocities measured at lookout points on major peaks and those prevailing in the lower surrounding plateau. The data were obtained by using recording 3-cup anemometers placed on two lookouts and also above the timber stand at Pilgrim Creek Nursery. Records gathered during two field seasons gave the degree of correlation existing and typical seasonal and diurnal velocity curves. Additional work in this study will be confined to securing a limited amount of automatically recorded data.

Fuel Studies

The failure of wind and fuel moisture to explain entirely the rate of spread of flat fires in ponderosa pine and subsequent observations in the field indicated that variation in the arrangement and distribution of fuel within this type was sufficient to materially influence rate of spread.

Several hundred small fires under laboratory conditions have resulted in the conclusion that the expression $\frac{V}{S}$ or the ratio of voids between fuel particles to surface area of the fuel is a satisfactory measure of the influence of fuel arrangement and distribution upon rate-of-spread in pine needle litter. The approximate ranges of this variable as it occurs in the field have been determined for the needle litter of ponderosa, sugar, and lodgepole pines. No direct method of measurement of this variable in the field has been developed, but fuel values have been obtained by comparing rates of spread in the field with no wind, with those obtained for known $\frac{V}{S}$ values with the same moisture content in the laboratory.

Studies are being conducted currently in the laboratory with different kinds of artificial fuels of regular sizes and shapes to check the conclusion that the ratio $\frac{V}{S}$ is the best measure of fuel distribution as it influences rate-of-spread, and to extend the range of experimental $\frac{V}{S}$ values previously obtained.

To determine whether chemical differences between various litter fuels might be responsible for differences in behavior, the heat values, percentages of volatile materials, and specific gravities of several types have been determined. No significant differences have been found.

A preliminary study was conducted in the field during the 1937 season to determine the feasibility of analyzing the quantity and size of fuels found in the northern California brush type as a basis for classifying fuel variations. Analyses were made of the fuels present on a number of milacre plots, but whether quantity fuels of different kinds and sizes can be used as a measure of the fuel characteristics which influence rate-of-spread has not been determined.

VI. CLARIFICATION OF OBJECTIVES AS DICTATED BY FIRE CONTROL NEEDS

Since the purpose of forest research is to provide factual information of use in the solution of problems in the field of forest management, a program of forest fire behavior study should be governed by the need for understanding those phases of fire behavior which contribute most to the protection problem.

Current Problems Requiring Fire Behavior Study

Forest fire protection in the United States is a relatively new activity. For this reason present methods and practices are largely based upon personal experiences and upon the successes and failures indicated by the analysis of past performance. These analyses can rarely be complete because all the elements which contributed to the successes or failures were not recorded, either through failure to recognize them, or because all factors can not be measured. There are, therefore, many problems facing the fire control administrator which depend to a large measure for their solution upon the accumulation of additional factual information through carefully planned and applied research. Among the more important of these problems are:

1. Determination of speed and strength of attack needed for adequate protection, which will aid in the proper planning of:
    - (a) Location and number of lookouts
    - (b) Design of transportation system
    - (c) Number and distribution of initial and secondary attack forces
    - (d) Communication requirements
    - (e) Distribution of improvements and equipment
2. Fire danger rating:
    - (a) Interpretation of fire weather measurements and forecasts
    - (b) Development of fire danger rating systems
3. Improvement in fire dispatching
4. Improvement in fire strategy and tactics
5. Determination of light burning and hazard reduction policies
6. Provision of classified knowledge for training short-term personnel
7. Determination of economic limits of fire protection
8. Determination of policy as to fire control practice
9. Determination of fire regulation, legislation, and other fire prevention activities

In addition to the above list of immediate pressing problems, there is a definite need for building up a store of behavior knowledge to supplement that gained by experience for the training and development of fire control personnel, and to provide a fundamental background for planning activities.

Contribution of Specific Behavior Studies to the Problems Listed Above

As indicated earlier, the purpose of all fire behavior research is to provide information which will contribute to the solution of fire control problems. The results of any specific fire behavior study may, however, contribute only indirectly to these problems as they aid in the development of other more practical studies. Examples of this type of contribution are found in the fundamental group of studies. Such studies as forest fuels, fuel moisture, and fire weather, although adding to the general store of knowledge, are of application to the solution of fire problems only as they provide the basic information upon which ignition, spread, and other studies may be founded.

Ignition and rate-of-spread studies, on the other hand, provide results of direct application in one or more of the problems enumerated. For example, ignition studies, concerned with the determination of the influences of weather and fuel factors upon the probability of fires starting, are aimed directly at problems confronted in the rating of fire danger and in various phases of fire prevention. Similarly, rate-of-spread studies concerned with the evaluation of the influences of such factors as wind, fuel moisture, fuel character, and topography upon the rate of spread of fire are recognized as essential to the solution of such problems as determination of speed and strength of attack, fire danger rating and other fire control problems. Miscellaneous behavior studies are aimed primarily at improving fire suppression strategy and tactics.

VII. RESEARCH POLICY

The objectives of a long-term fire behavior research program should be founded upon the primary fire control problems as far as they can at present be deduced, and the place of the research unit in the nation-wide attack on the problem.

Place of Behavior Studies at the California Station in the Solution of Local and National Fire Control Problems

All of the fire control problems listed in the foregoing section are of broad application and national significance. Only the first two directly require the expression of specific results in terms of Region 5 conditions, and even these will permit generalizations of wide-spread application. Thus it is apparent that great opportunity exists for noteworthy contributions from both national and local viewpoints.

At the Mount Shasta fire research conference of September 1936, the need for a concerted program of basic research was recognized by all the Experiment Stations represented. At that time the general program proposed in this report for the California Station was agreed upon by those participating in the conference for two reasons: first, because considerable progress had already been made here on several fundamental problems; and second, because the facilities and personnel of the California Station were in the best position to carry on a fundamental fire behavior research program.

Thus the long-term California fire behavior program will be guided by the following principles:

1. Basic information is essential to the general advancement of fire control practice.

2. The fire control problems of the California Region are of first priority and the research program will be aimed specifically at their solution.

3. Basic or fundamental research on these problems will be conducted in sufficient detail to result in the general and permanent application of the principles and methods obtained.

Long-term Behavior Research Objectives

Two problems are of particular importance in the development of fire control practice in California: first, determination of speed and strength of attack required for adequate fire protection; and second, determination of methods of rating and interpreting fire danger. Two groups of behavior studies contribute to their solution and shall, therefore, constitute the long-term behavior research objectives at the California Station. These are:

1. Determination of the influences of the major physical factors on the rate-of-spread of fires; and

2. Determination of the influences of the major physical factors on fire ignition.

Practical vs. Fundamental Approaches to Behavior Research Problems

There are two possible research methods of approach to the solution of these objectives. The first is a direct approach through study of the problems in the field under the natural conditions where the results are to be applied. Outstanding examples of this method include such studies as analyses of fire records, and the observation of test fires in different fuel types to determine probable rates-of-spread under specific conditions of weather and topography, for direct application to those types. The observation of going fires is another example of the practical method of approach in studying rate-of-spread.

The second method of approach is based upon the conception that the end result of the interaction of any series of factors is determined by certain physical laws which govern the influence and behavior of each individual factor. In this method, the first step is to analyze the problem and to divide it into its many components for individual study. Following this initial analysis, the steps that logically follow are: (1) determination of the factors which influence the problem; (2) development of methods of measurement of each factor; (3) determination of the fluctuations and variations of each factor under natural conditions; (4) determination of the influence of each factor throughout the range of its natural variation individually and in simple combinations; and finally, (5) correlation of the influences of all the factors upon the problem.

Each of the two methods applied separately has several advantages and disadvantages which must be given consideration in the solution of any specific objective in a research program. The principal advantages of the practical method are that end results, although rarely conclusive, are attained relatively quickly and that a fundamental background is not entirely essential. Its disadvantages on the other hand are: (1) results are normally only of local application; (2) only superficial results are obtained usually in terms of indexes rather than in terms of measurable quantities; (3) they provide a limited chance at best for contribution toward a sound scientific basis; (4) it is a trial and error method in which much data collected cannot be used to advantage; and (5) it is frequently necessary to await desired conditions when making field tests.

The advantages of the fundamental method of approach are: (1) it is based on logic; (2) it determines fundamental principles of wide application; (3) it contributes to the general wealth of scientific knowledge; (4) the end results are applicable in a large measure quantitatively; and (5) they form a scientific background for further studies in allied fields. The disadvantages of the method are: (1) it is slow and end results are not immediately available; (2) it frequently requires expensive equipment to provide experimental controls; (3) it requires a more specialized and highly-trained personnel; and (4) without intensive supervision it tends to stagnate or to branch off on studies which do not contribute materially to the major problem.

The policy of the California Station concerning the choice of research methods in the solution of long-term fire control problems will be governed largely by application of three important considerations to these advantages and disadvantages. First, and most important, is the consideration of California fire-control problems of first priority and the possibility of contributing materially to their solution through practical research activities. Second is the consideration of the personnel and facilities available for the conduct of various types of fire research, and third, the obligations of the California fire research unit imposed by reason of the part it must play in the national program.

A study of these considerations indicates: first, insufficient knowledge of fundamental principles of fire behavior upon which practical studies of major fire control problems can logically be based; second, present personnel and facilities are about equally adapted to each method; and third, while results of direct local application are the immediate aim, sufficient fundamental research should be conducted to provide the necessary basis for similar studies in other regions.

A policy involving a combination of the practical and fundamental approaches, therefore, is accepted as a guide in meeting the long-term research objectives. Fundamental research methods will receive special emphasis because it is recognized that none of the major problems can be completely solved without a large amount of additional basic information. Such fundamental research will, however, be specifically limited to studies of basic principles essential to the solution of the major problems. Measures will be taken, on the other hand, to advance as rapidly as possible the attainment of practical results by bridging gaps to be filled in later by detailed fundamental study.

The research program developed in the following section is based upon the above policy. Fundamental studies are stressed insofar as they are deemed essential to continued progress, while at the same time, certain practical studies aimed at immediate solution of outstanding rate-of-spread problems occupy a prominent place.

VIII. THREE-YEAR BEHAVIOR RESEARCH PLAN

General

In the foregoing section, the general objectives of the fire behavior research program have been established as the determination of the influences of the major physical factors on (1) rate-of-spread, and (2) ignition. It is now desirable to determine the study priority which appears to offer the most logical and effective means to attain these objectives. Establishment of priorities in this type of research is difficult and if strictly enforced, ineffective, because of the impossibility of establishing definite study completion dates, and because of the interrelationships between studies. The following priorities have been established, nevertheless, as a general guide to research during the next 3-year period. This priority list does not contemplate the conclusion of one study prior to the completion of the next but should serve rather as a guide to relative distribution of effort among the studies listed. This analysis is not concerned with the detailed approach which should be covered by individual study work plans.

1. Physical fuel characteristics.

In this analysis the lack of understanding of the physical characteristics of fuels influencing fire behavior has been shown to be an outstanding problem. It is obvious that without a clearer knowledge of the influence of this factor, the field of all fire behavior research and particularly spread research, is limited. Accordingly, first priority is assigned this study.

Continuation of the present research approach is contemplated. Three general methods appear to offer results: (1) the development of an inexpensive, portable wind tunnel for continuation of laboratory studies with the added factor of wind velocity; (2) field studies in complicated fuel types with experiments designed to show the influence of removing or adding fuels of various classes, and (3) the continuation of laboratory tests with artificial fuel. The need of an improved fuel classification for fire planning should be in mind as one concrete possibility of contributing to current fire control practice.

2. Fuel moisture.

A second study of application to all phases of fire behavior research is the determination of the causes and ranges of moisture fluctuation in fuels, both dead and living. Data on this phase of the problem are urgently needed for immediate application to fire danger rating. For these reasons, continuation of the study already under way in this field is contemplated.

The principal objectives sought in this study are:

1. Determination of the influence of weather factors upon:

   (a) Fine litter fuel moisture

   (b) Common green fuel moisture

2. Influence of cover density upon fuel moisture

3. Correlation of fuel moisture data with fire danger rating measurements

Present methods of approach are considered logical and satisfactory. Work for this period will be confined to the brush and ponderosa pine types.

3. Test Fires.

Continuation of the test fire program is planned with main emphasis on the brush type. Test fires are an invaluable accompaniment of the fundamental studies in indicating the relative importance of factors to be studied and in providing a means of testing fundamental theories and methods. In addition, continued study of brush fires promises to permit generalizations of immediate practical value on the spread of fire in this type.

In the study of fire behavior, some thought has sometimes been given to the advantages of studying rate of spread in grass. The lack of an annual grass type on the Shasta Experimental Forest has resulted in neglect of this approach. If the fuel studies progress to a point where studies in a simple type are considered desirable, arrangements may be made for a series of test fires at Davis or some other valley location.

The technique of test fire study has been developed to a satisfactory degree and no major changes are suggested. Because of its ease of measurement and wide application under all conditions, the use in the future of "forward spread" in place of perimeter as the dependent variable is recommended.

4. Fire Ignition.

In the development of fire danger rating in California, reliance is placed on the fire behavior project to provide data on the influence of measurable weather upon both spread of fire and fire ignition. Satisfactory progress is being attained toward the first objective, but to date little or no research data are available on the second. An exploratory study is established, therefore, in this priority on the subject of fire ignition. A practical, rather than a fundamental approach is contemplated, giving emphasis to: (1) a rough classification of fuels from an ignition standpoint; (2) a similar classification of firebrands; and (3) tests of firebrands and fuels through the normal range of fuel moisture. This will be conducted primarily as a field study.

5. Wind measurement.

In a previous section of this analysis, the current advances made in wind measurement and wind behavior have been summarized. Although present commitments prevent continuation of this study on a similar scale in the future, a small program of study is contemplated. Only such studies will be undertaken as can be designed about the recording instruments available. The study will be managed to prevent interuption of work of higher priority and will consist chiefly of studies designed to show the influence of topography and cover on wind movement. In the application of fire behavior data to rating fire danger, the location of anemometers is an important practical problem. Continuation of present studies for this purpose, primarily, is contemplated.

6. Going fires.

Although the present knowledge on fire behavior is largely the result of fire suppression activity, studies of going fires have resulted in little data of consequence in generalizing on fire behavior problems. This paradox results from the fact that observations made in the field can seldom be complete, but with long experience men can arrive at conclusions which, though unsupported by measurement, comprise the useful background possessed by the experienced fire fighter. The study of going fires undoubtedly offers possibilities of improving fire behavior knowledge if a satisfactory study technique can be developed.

Two unusual opportunities for the study of going fires exist; the first in connection with the current mapping of fires in southern California, and the second, on the Shasta National Forest, as a phase of the scouting of large fires handled largely by Experiment Station personnel. It has been decided to establish studies in both sections, primarily, at first, for the development of methods. Accurate maps of the spread of going fires should be sought with concurrent information on fuel moisture and weather factors. The possibilities and limitations of such studies should be determined.

7. Topography.

Opportunity exists for the improvement of knowledge of the influence of topography as a result of two studies planned for other purposes. The first of these, the fuel study, will provide equipment useful in the study of the combined influence of wind and slope on spread. The importance of such a study has been emphasized by the data obtained in the ponderosa pine type. Another possibility for securing information on the influence of topography is the study of going fires.

Summary

The studies of priority one, two, and three will be pursued regardless of the resources available. Comprehensive attack on the fourth must await additional technical assistance. The remainder are of secondary importance and warrant only incidental attention.

IX. ASSIGNMENT OF STUDIES

Responsibilities of men assigned to studies

The preceding section of this analysis sets up priorities, objectives, and general methods of approach for the individual studies in the succeeding 3-year research program. Each individual to whom a study is assigned, however, will be entirely responsible to the project leader for: (1) the development of a work plan; (2) conduct of the experimental work; and (3) analysis and report of results.

Assignments

The assignments listed below are for the ensuing 3-year period or for the duration of a study, in the event it is completed within the period.

1.	Forest fuels	W. L. Fons, in charge R. K. Blanchard
2.	Moisture content	C. C. Buck
3.	Test fires	C. C. Buck, in charge W. L. Fons and R. K. Blanchard
4.	Fire ignition	R. K. Blanchard
5.	Wind measurement	W. L. Fons
6.	Going fires	
	(a) Southern California	C. A. Abell
	(b) Shasta National Forest	C. C. Buck, in charge W. L. Fons and R. K. Blanchard
7.	Topography	R. K. Blanchard

X. WORK PLAN DEVELOPMENT

The preparation of written work plans is a recognized standard practice in forest research. The purpose of this section is primarily to clarify the relationship between work plan development and the objectives set up in the foregoing analysis. In no sense is it intended to standardize thought on the part of those responsible for the conduct of individual studies, but rather to serve as an aid by pointing out the important elements which should be considered in any work plan. Neither is it intended that this listing of work plan elements serve as a stereotyped work plan outline.

General

A work plan may be defined as a combination of problem analysis and job listing. Its purpose is, first, to define the problem to be investigated, and then to set down in orderly fashion the necessary steps required to attain the objective. In fire behavior research, the individual studies as enumerated in the three year research program shall constitute the work units for which work plans will be developed.

Elements of a Work Plan

A work plan as an efficient research tool must provide for adequate consideration of a number of important elements. Those deemed essential and which should be treated in every work plan are enumerated below:

1. Scope of the study
2. Broad objectives
3. Specific objectives
4. Immediate objectives of current attack
5. Status
6. Method of approach
7. Job list for current work period
8. Summary and analysis of data
9. Reports
10. Time and personnel requirements
11. Personnel assigned and responsibilities

Work Plan Revisions

Work plans will normally be written for the duration of a study or for the duration of the three-year planned program where the study may be expected to carry beyond this period. Because of the exploratory character of much of the current work, it is impossible to foretell the exact course to be followed for long periods. For this reason adequate provision should be made in all work plans for periodic and current revisions as progress is made in solution of the problems.

XI. ANNUAL WORKING PLAN CONFERENCE

Once each year a conference of those actively engaged in fire-control and fire research within the region will be held for the express purpose of reviewing current results, for scheduling publication, and for establishing current study priorities.

The specific jobs to be accomplished at each conference are:

1. Review current accomplishments
2. Select material for publication and schedule the manuscript writing
3. Revise study priorities and assignments where necessary
4. Agree on jobs for succeeding field season.

APPENDIX I

Principal Factors Influencing Fire Ignition

1. Fuel

   (a) Kind of fuel
   (b) Physical characteristics
   (c) Chemical composition
   (d) Moisture content of fuel
   (e) Temperature of fuel

2. Weather

   (a) Humidity of air
   (b) Temperature of air
   (c) Oxygen supply
   (d) Wind velocity

3. Fire brands

   (a) Kind
   (b) Size
   (c) Thermal characteristics

4. Time

   (a) Length of exposure

APPENDIX II

Principal Factors Influencing Rate of Spread of Forest Fires

1. Fuel

   (a) Kind
       Species
       Condition (green, dry)

   (b) Moisture content
   (c) Composition
       Chemical
       Heat content

   (d) Physical characteristics
       Size
       Shape
       Density
       Arrangement
       Surface condition
       Specific heat

2. Weather

   (a) Humidity of air
   (b) Wind velocity
   (c) Air temperature
   (d) Barometric pressure
   (e) Clouds and inversion layers
   (f) Insolation

3. Topography

   (a) Slope
   (b) Exposure
   (c) Saddles
   (d) Canyons and draws
   (e) Natural barriers
   (f) Continuity of topographic features

4. Time

   (a) Cumulative effects of time